ILMENITE-HEMATITE-MAGNETITE RELATIONS IN SOME EMERY ORES

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ABSTRACT

The principal mode of occurrence of hematite and ilmenite in emery ores from a number of localities is in the form of unique exsolution intergrowths, suggesting unusual crystallization-temperature-solution conditions. Magnetite, not a component of these exsolution intergrowths, is the most abundant opaque constituent in some polished sections, but is rare, or totally absent, in others. Ilmenite exsolves from hematite to sharp magnetite-hematite boundaries, showing that much of the hematite now present crystallized originally as hematite, and is thus not a later replacement product of magnetite. Some replacement of magnetite by hematite is noted, but only a minor percentage of the total hematite present has formed in this manner.

Ilmenite of one age often exsolves parallel to two crystallographic directions within hematite. In addition, two readily distinguishable ages of exsolution ilmenite in hematite are often observed. The ilmenite bodies of each age have a characteristic orientation in the hematite. The original solid solution varied in composition from dominant hematite to dominant ilmenite.

Exsolution of hematite from corundum is well shown in some sections. In those ores in which the corundum exhibits parting, hematite exsolved both as blebs and as needles, and in the ores in which the corundum does not exhibit parting, hematite exsolved only as minute blebs.

INTRODUCTION

In the literature concerning emery deposits, much discussion is devoted to genesis and to the relations between the nonopaque minerals. The relations between the opaque minerals have been only casually mentioned, and it was with this fact in mind that the writer undertook the present study. Ores from the following places were used for study: Naxos, Greece; Whittles, Virginia; Chester, Massachusetts; Macon County, North Carolina; and Peekskill, New York. Interesting exsolution relations between ilmenite and hematite were found to be universal, and will be stressed in the descriptions to be given. Some of the features observed are believed to be peculiar to emery ores.

The only previous reference to exsolution structures in ores of this type, so far as the writer is aware, has been by Butler,[1] who merely noted their presence in the ores from Peekskill, New York. The author is deeply indebted to Professor W. H. Newhouse, who suggested this work, and who freely gave helpful advice and criticism. Thanks are due Dr. Arthur C. Bevan, State Geologist, Virginia Geological Survey,

[1] Butler, J. W., *Am. Mineral.*, **21**, 537–575 (1936).

who kindly furnished several specimens from Whittles, Virginia. William Parrish, of the Massachusetts Institute of Technology, rendered constructive criticisms and suggestions, and John A. Shimer aided in reading the manuscript.

Descriptions and Discussion

Ores from Naxos, Greece

General

The major portion of the ore is an aggregate of subhedral to anhedral grains of corundum, some of which are as large as 2 mm. in diameter. The corundum does not show parting. Minor small patches of hematite are present interstitially to and molded around corundum grains. The greatest dimension of any of the hematite masses measured was 1.2 mm. The hematite universally contains very minute exsolution lamellae of ilmenite. No ilmenite is present as grains, and magnetite is totally absent in the material examined.

Hematite-ilmenite exsolution relations

Because of the small size of a majority of the hematite grains, and due to the minute scale of the ilmenite exsolution, high magnification was necessary to bring out the hematite-ilmenite relations. Every patch of hematite contains minute exsolution lamellae of ilmenite, which commonly lie in one, two or three directions within hematite. The thickness of ilmenite lamellae lying in different directions frequently varies. At times the exsolution lamellae widen laterally. Exsolution of ilmenite to borders of hematite crystals is common.

The patterns formed by exsolution lamellae appear rectangular, rhombohedral, or a combination of both. Comparatively thick, tapering bodies of ilmenite commonly lie at approximately right angles to thin, hair-like lamellae. This pattern is often modified by the presence of a third set of thin lamellae, inclined at approximately 45° to both sets first described. All the ilmenite appears to be of the same age. The exsolution blades of ilmenite presumably lie parallel to (0001)[2] and to rhombohedral directions within hematite. These unusual exsolution intergrowths indicate one of several possibilities: first, the hematite now present is a product of a wholesale replacement of magnetite, preserving exsolution structures of ilmenite in the replaced mineral; or second, the present hematite existed in an original solid solution as hematite, and exsolution of ilmenite took place in an unusual manner.

[2] Ramdohr, P., *Festschr. Bergakad. Clausthal*, 307–340 (1925). Ramdohr, P., *N. Jahrb. Min., Bd.* **54,** 320–379 (1926).

Although ilmenite has been previously described as exsolving parallel to only one direction (0001) in hematite, the second possibility mentioned above seems much the more reasonable when all evidence is considered. First, no magnetite was found in the material examined. If replacement of magnetite by hematite was actually responsible for the ilmenite patterns seen, the replacement was unusually complete. Second, the presence of exsolution ilmenite at hematite crystal boundaries indicates that the present borders of the hematite crystals were the original borders. Third, the patterns found are never in the form of complete equilateral triangles, as would be expected if the ilmenite was preserved by a replacement of magnetite. Instead, exsolution ilmenite lamellae frequently lie in but one direction, or they form rectangular or rhombohedral patterns. Where combinations of the two latter patterns are present, the result in no way simulates a set of equilateral triangles. The great predominance of hematite over ilmenite in the intergrowths indicates that the original solid solution was very much richer in hematite than in ilmenite.

Exsolution of hematite from corundum

Hematite not only occurs as patches and grains, as previously described, but also as minute blebs within corundum grains. Close examination reveals that these blebs are concentrated in especial abundance, as swarms, toward the centers of certain subhexagonal corundum grains. The maximum diameter of any hematite bleb is 0.03 mm., and the average diameter is in the neighborhood of 0.005 mm. Some of the blebs exhibit a roughly hexagonal form. Their occurrence and distribution suggests their origin as an exsolution product from corundum.

Ores from Whittles, Virginia

General

The ore is fine grained, and is indistinctly banded. Pink bands in which ilmenite is the dominant constituent alternate with bands in which corundum and magnetite predominate. Corundum occurs as irregular grains and masses, but frequently shows angular boundaries. The maximum measured diameter of any corundum grain was 0.4 mm. The nonopaque constituents are slightly more abundant than the opaque minerals. No tendency for the corundum to exhibit parting was observed.

Magnetite and ilmenite occur as irregular grains, molded around and between corundum grains. The maximum measured dimension of magnetite was 0.6 mm., and for ilmenite 0.2 mm. Magnetite is somewhat more abundant than ilmenite. Hematite is present only in minor quantity, existing as fine, parallel exsolution lamellae in ilmenite, and as a replacement product of magnetite.

Hematite-ilmenite-magnetite relations

The exsolution hematite occurs as very minute lamellae lying in one direction within ilmenite. This type of exsolution is a good example of the common exsolution parallel to the basal pinacoid.[3,4,5] The replacing hematite occurs in the form of equilateral triangular patterns in the vicinity of fractures and boundaries of magnetite grains. Contacts between magnetite and ilmenite are sharp and distinct. The relative quantity of the two solid phases in the intergrowths shows that the ilmenite-hematite solid solution was in this case exceedingly rich in ilmenite (Ti) and poor in hematite (Fe).

Exsolution of hematite from corundum

Exsolution hematite within corundum occurs as very minute blebs, often beautifully aligned. In some corundum grains, lines of hematite blebs lie in two directions, and in other corundum grains, in three directions. Lack of definite data here renders impossible the accurate determination of the orientation of the exsolution hematite.

Emery Ores from Chester, Massachusetts

General

Polished surfaces reveal a fine banding of the opaque and nonopaque minerals. Corundum is not abundant, occurring as irregular grains with an average diameter of about 0.5 mm. Several corundum grains exhibit excellent rhombohedral parting and twinning. Much of the corundum has been considerably altered. Magnetite occurs as numerous subcircular to subelliptical, worm-like masses which appear to corrode the corundum.

Magnetite is also present as numerous angular grains, up to 1.3 mm. in diameter. Hematite is usually interstitial to magnetite grains, and is about one tenth as abundant as the latter. The larger hematite grains measure about 0.10 mm. in diameter, and always form parts of intricate exsolution intergrowths with ilmenite. Magnetite is not a component of these intergrowths.

Hematite-ilmenite-magnetite relations

There are two distinct types of exsolution ilmenite present within hematite. First, a salmon-colored ilmenite, which occurs as irregular

[3] Ramdohr, P., *loc. cit.*

[4] Schneiderhöhn-Ramdohr, Lehrbuch der Erzmikroskopie, Bd. **2**, 539–550 (1931).

[5] Schwartz, G. M., *Econ. Geology*, **26**, 739–763 (1931).

plate-like masses and thick lamellae. Second, a later, cream-colored ilmenite, which occurs as thin blades and as irregular masses at the boundaries of hematite grains and crystals. That the cream-colored ilmenite exsolved later than the salmon-colored ilmenite is proven in many cases where blades of the later ilmenite crosscut plates or thick lamellae of the earlier, darker ilmenite, or project into "embayments" in the latter. The later ilmenite also piles up against plates or lamellae of the earlier ilmenite.

The early ilmenite usually contains a further exsolution of hematite as minute blades parallel to the lengths of ilmenite plates or lamellae. This strongly suggests that the early ilmenite exsolved parallel to the (0001) direction in hematite. That this is the case is shown by the fact that the hematite shows maximum extinction, in polarized light, parallel to the lengths of the earlier ilmenite bodies (the position of maximum extinction for hematite is parallel to the (0001) direction). In polarized light, the bodies of both types of ilmenite show extinction parallel to their longer dimensions. The later, light-colored ilmenite often exsolved in two directions within hematite, and a rhombohedral pattern similar to that shown in Fig. 1 was the result. The orientation of the later ilmenite appears to be, then, parallel to the rhombohedral directions in hematite. (Since the earlier ilmenite lies parallel to (0001) in hematite, and since the longer dimensions of the later ilmenite are different from those of the earlier ilmenite, the blades of later ilmenite are certainly not oriented parallel to (0001) of hematite.) The thickness of blades parallel to one rhombohedral direction is commonly greater than that of the blades in the other rhombohedral direction. This may be due to the orientation of the polished sections.

In cases where the later ilmenite exsolved parallel to two directions in the same hematite grain in which earlier ilmenite was present, a pattern like that shown in Fig. 2 was the result. One set of blades of the later ilmenite are seen lying at about right angles to the direction assumed by the earlier, darker ilmenite.

Ilmenite forms a large proportion of the material present in the intergrowths, which shows that the original solid solution was quite rich in ilmenite. The earlier, dark ilmenite appears to be normal ilmenite, but the lighter, later ilmenite is apparently a variety rich in Fe_2O_3. The cream-colored ilmenite is much more resistant to hydrofluoric acid than is the darker variety, and sometimes shows a slight internal reflection. Otherwise, the properties of the two are identical. No replacement of magnetite by hematite was noted in the material examined, and this fact, together with the observation that exsolution ilmenite from hematite was usually present at hematite-magnetite boundaries and at hematite crystal boundaries, seems to indicate that the hematite now present was originally present in a solid solution as hematite, and therefore did not form as a replacement product of magnetite.

Ores from Macon County, North Carolina

General

The opaque and nonopaque minerals are here present in approximately equal proportions. The ore consists of alternating crude bands of corundum and opaque minerals. The corundum occurs as subhedral to anhedral grains up to 2.5 mm. in diameter, and often exhibits very well developed rhombohedral parting and twinning. Scattered small grains of hematite occur within corundum. In the bands composed mainly of opaque minerals, hematite occurs in irregular grains up to 2 mm. in diameter. Magnetite, about one half as abundant as hematite, is also present in these bands as very irregular grains, the largest of which are about 0.5 mm. in diameter. The magnetite tends to occur toward the margins of the bands. Ilmenite is present in great abundance as exsolution intergrowths within hematite. The hematite sometimes possesses twinning.

Hematite-ilmenite-magnetite relations

Here again the exsolution ilmenite is of two ages. The early, darker ilmenite occurs as small, irregular, subrectangular to subtriangular masses, which are aligned parallel to one direction in hematite. The later, lighter-colored ilmenite is similar to that described in the Chester, Massachusetts, ores. Figures 1 and 2 again may be used to illustrate typical relations between hematite, ilmenite, and magnetite. Here again evidence indicates that the early ilmenite exsolved parallel to the (0001) direction of hematite, and that the later ilmenite exsolved parallel to rhombohedral directions.

A strip of lighter ilmenite is commonly found at hematite-magnetite contacts, and at hematite crystal boundaries. This fact suggests that the present boundaries between magnetite and hematite were the original boundaries between these two minerals. The original hematite-ilmenite solid solution contained about twice as much hematite as it did ilmenite. Some replacement of magnetite by hematite along octahedral directions was noted, but only adjacent to fractures in the magnetite, or at corundum-magnetite contacts. This type of hematite is very minor in quantity.

Exsolution of hematite from corundum

Numerous minute needles of hematite can be seen crosscutting the parting and twinning directions of corundum at angles of about 45°. These needles lie parallel to the lengths of corundum grains. It appears as though these hematite needles originated as an exsolution product from corundum, and lie parallel to the *c*-axis of the latter. The needles of hematite appear identical to those shown in Fig. 4.

Ores from Peekskill, New York

General

Nonopaque minerals greatly predominate over opaque minerals in the Peekskill ores. Irregular patches of metallic minerals occur interstitially to grains of several nonopaque minerals. The patches of metallic minerals often interconnect to form networks. Corundum usually shows rounded, irregular boundaries against the opaque constituents. The corundum exhibits parting.

Of the opaque minerals present, hematite and ilmenite are by far the most abundant. These minerals occur, as a whole, in approximately equal proportions, always intergrown one with the other. Hematite grains reach a diameter of 1 mm. Magnetite, minor in quantity, occurs as small, irregular grains up to 0.3 mm. in diameter.

Hematite-ilmenite-magnetite relations

Hematite and ilmenite universally exhibit exsolution intergrowths one with the other. The textures produced are rather coarse, because of the large proportion of ilmenite to hematite in the original solid solution. Coarse blades of ilmenite are found parallel to the (0001) direction in hematite. The exsolution blades of ilmenite always show a further exsolution of hematite blades parallel to their lengths, and hence parallel to their (0001) directions. In grains in which ilmenite predominated in the original solid solution, the relations just described are reversed. In cases where the solid solution contained equal proportions of hematite and ilmenite, a structure such as that shown in Fig. 3 was the result of mutual exsolution.

Ilmenite frequently exsolved from hematite to hematite-magnetite contacts. Where hematite was in contact with both magnetite and corundum, ilmenite usually exsolved to hematite-magnetite boundaries in preference to hematite-corundum contacts. Contacts between ilmenite masses and grains of magnetite are always sharp and definite, and no replacement of magnetite by either hematite or ilmenite was seen. Here again the hematite now present appears to have been present originally

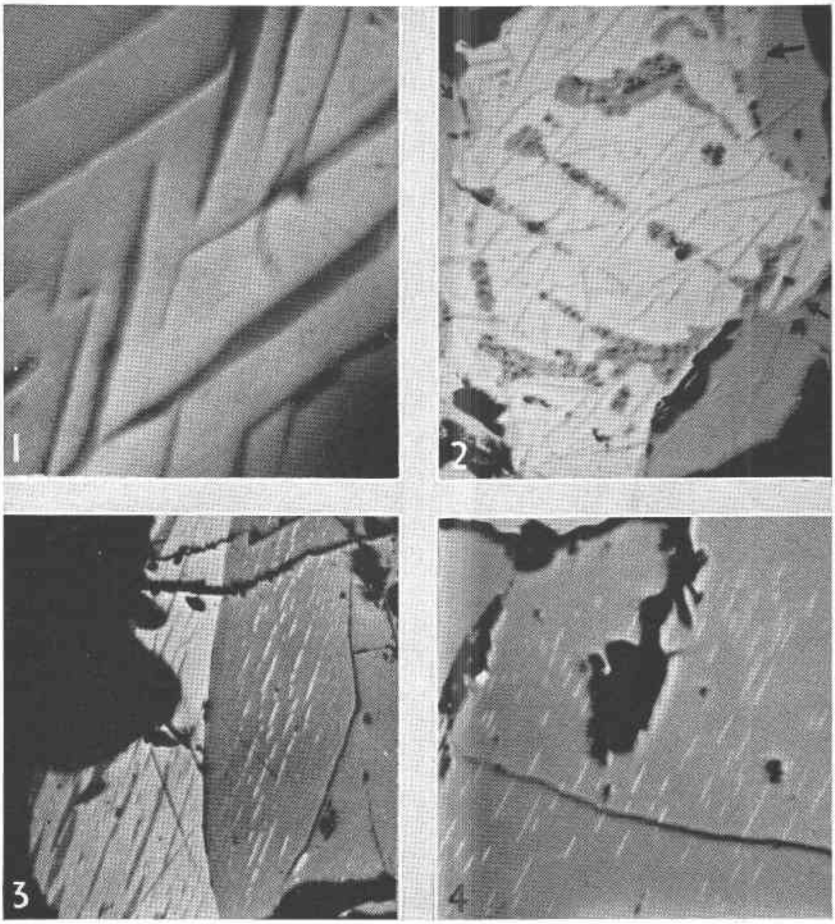

FIG. 1. Photomicrograph of blades of exsolution ilmenite (dark) in hematite (light) ×950. Note rhombohedral pattern formed by the exsolution blades. Locality: Macon County, North Carolina.

FIG. 2. Photomicrograph of exsolution ilmenite (dark) of two ages within hematite (light). ×230. Magnetite surrounds the hematite grain. Darker ilmenite is the older. Note exsolution of later ilmenite to form rhombohedral patterns, and "piling up" of later ilmenite at magnetite-hematite boundaries (see arrows). Locality: Chester, Mass.

FIG. 3. Photomicrograph of common exsolution structure in Peekskill ores. ×235. Hematite light, ilmenite dark (with exsolution blades of hematite), magnetite dark (lacking exsolution structure). Note parallelism of all exsolution blades. Locality: Peekskill, New York.

FIG. 4. Photomicrograph of exsolution needles of hematite in corundum. ×300. Locality: Peekskill, New York.

in a solid solution as such, and thus is not a later replacement product of magnetite. The original solid solution contained approximately equal proportions of ilmenite and hematite.

Exsolution of hematite from corundum

Numerous examples of hematite exsolution from corundum are present, both as tiny blebs and as needles (Fig. 4). The blebs and needles have characteristics identical with those previously described in other ores.

Summary and Conclusions

From the preceding discussion and descriptions, the following points may be emphasized:

1—In the emery ores examined, hematite is chiefly a primary mineral, and not secondary after magnetite. This is shown by the continual presence of exsolution ilmenite at the borders of the crystals. Hematite resulting from the replacement of magnetite is comparatively negligible in quantity.

2—In some of the ores examined, exsolution ilmenite in hematite is of two types: first, an earlier, dark-colored type, which exsolved parallel to (0001), and second, a light-colored variety of ilmenite, which apparently exsolved parallel to rhombohedral directions. The age relations are quite clear. This "two-stage" exsolution of ilmenite is quite different from the type described by Ramdohr, who advanced the "two-stage" explanation for exsolution bodies of ilmenite and hematite which existed only in the common (0001) direction.

3—Because of the exsolution relations seen in these ores, rather unusual temperature-crystallization-solution conditions must have prevailed during the formation of the ores.

4—The original solid solution varied in the various ores from dominant hematite to dominant ilmenite.

5—So far as the writer is aware, the following features are peculiar to emery ores: (a) The exsolution of ilmenite from hematite in several directions, forming rhombohedral patterns, and (b) the age-orientation relationships between exsolution ilmenite and hematite previously described under (2).

6—In ores where exsolution hematite exists only as blebs in corundum, the corundum does not show parting. Where exsolution hematite is present mainly as needles, the corundum exhibits parting.